Renewables + Storage Drop-in Replacement of Fossil Power Plants

ARPA-E Long-duration Energy Storage Workshop

December 7th, 2018

Problem Statement

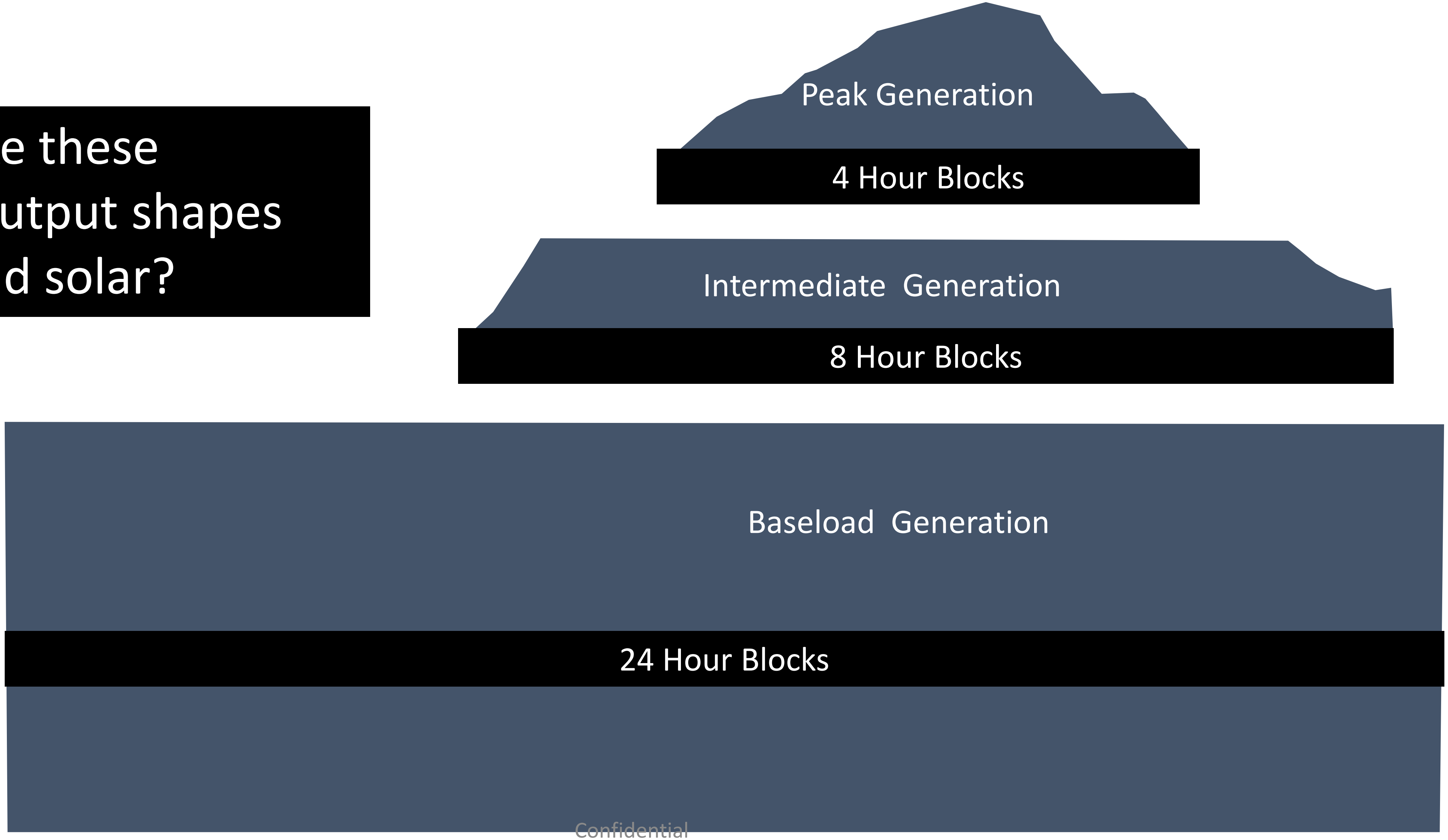
Decarbonizing electricity will require that low-carbon sources meet energy demand throughout the day. Wind and solar photovoltaics are possible technology options, but intermittency and seasonality can be challenges to cost-competitive deployment.

We analyze storage with wind and solar across four locations and four grid roles, determining which technology features are preferable for providing reliable output over twenty years.

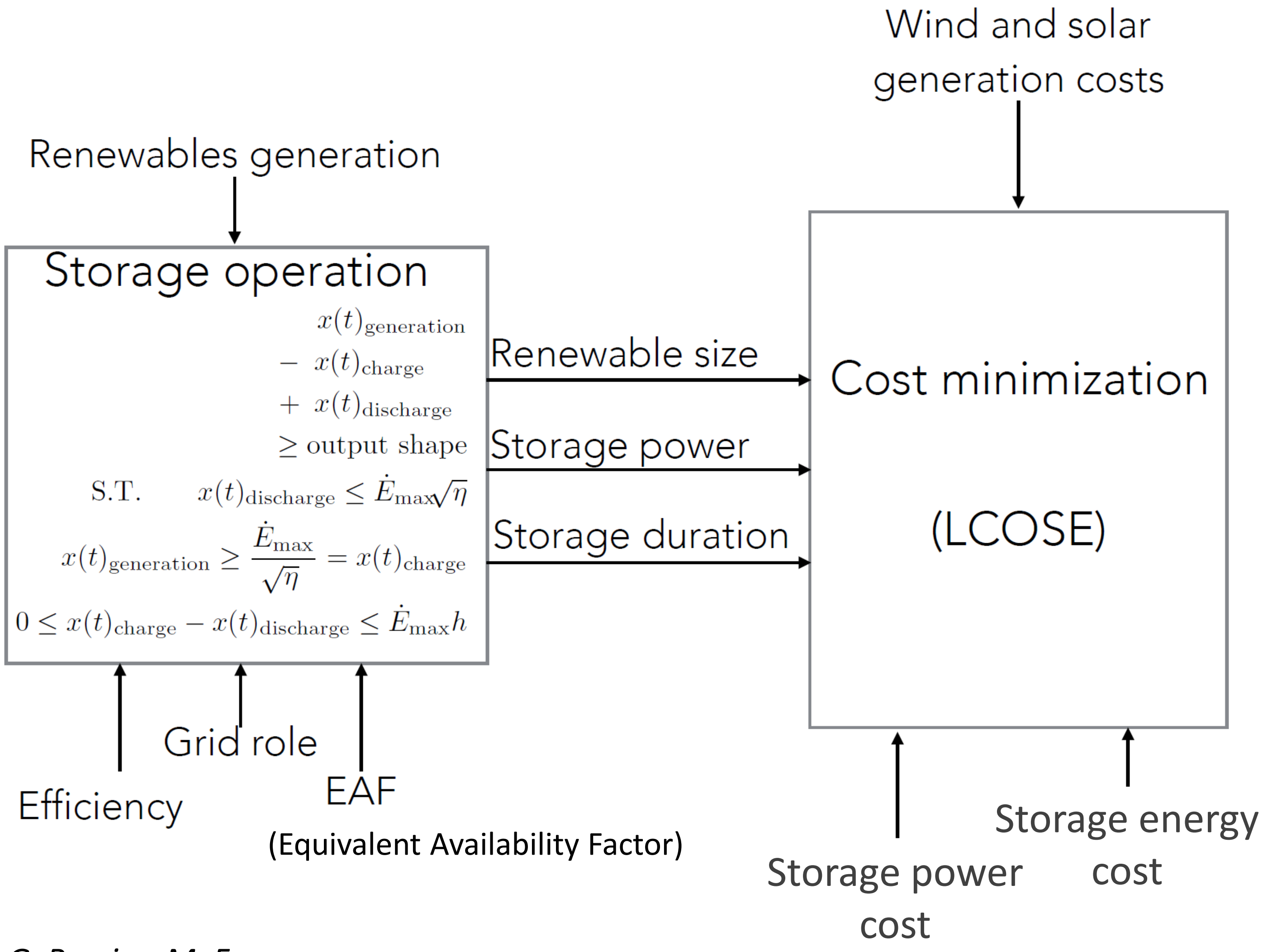
We find that storage with costs below $20/kWh and wind/solar can be cost competitive with conventional generation technologies. Sensitivity to storage power cost $/kW and round-trip efficiency are substantially weaker than to energy cost $/kWh.

Traditional Generation Output Shape

Can you make these generation output shapes with wind and solar?

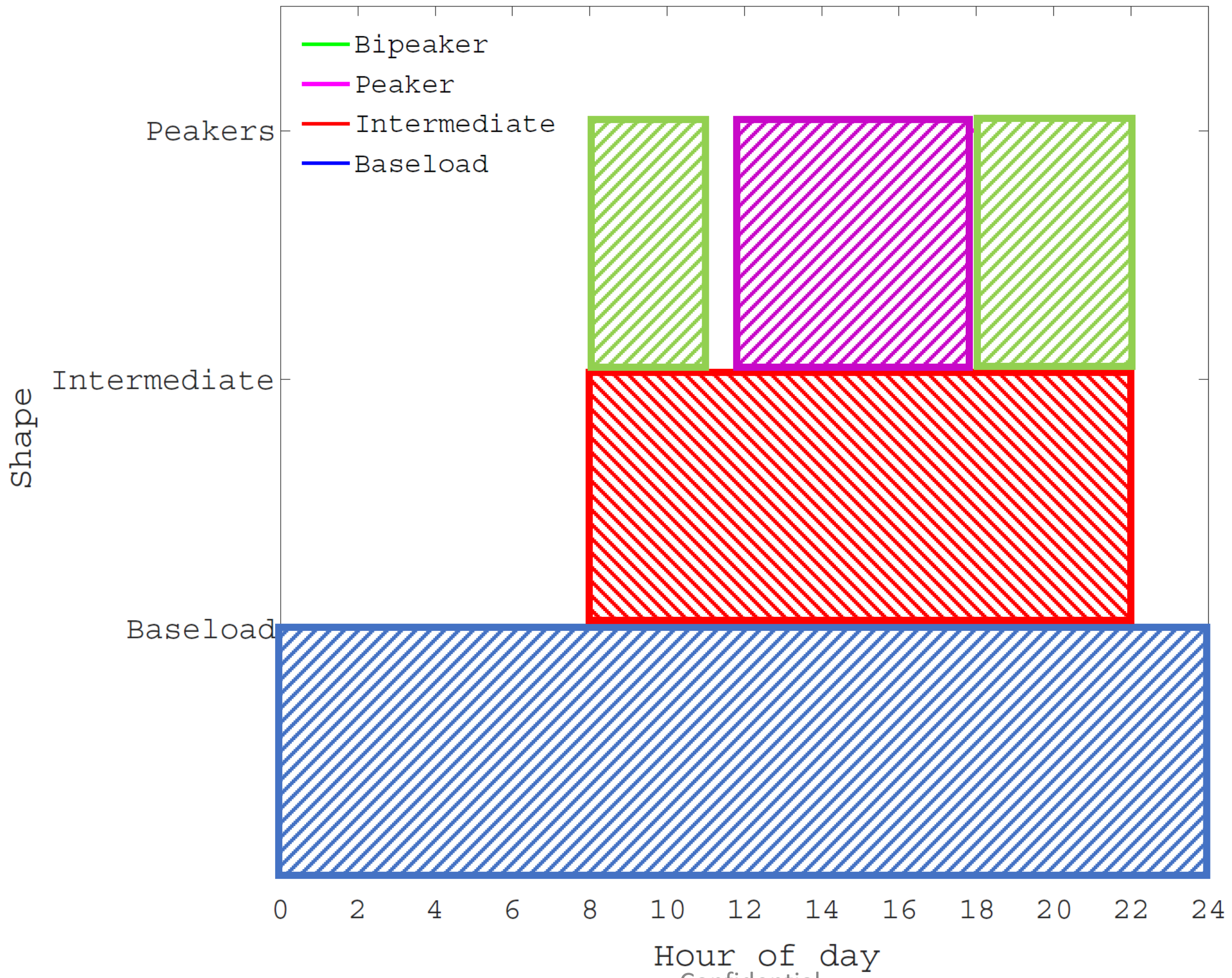


Analytic Framework*



*J.M. Mueller, G. Pereira, M. Ferrara
J. Trancik, Y.-M. Chiang, MIT 2017

Four Simplified Grid Roles Were Chosen For The Analysis



Example: Baseload Generation From Wind

First of its Kind Peer Reviewed Study*

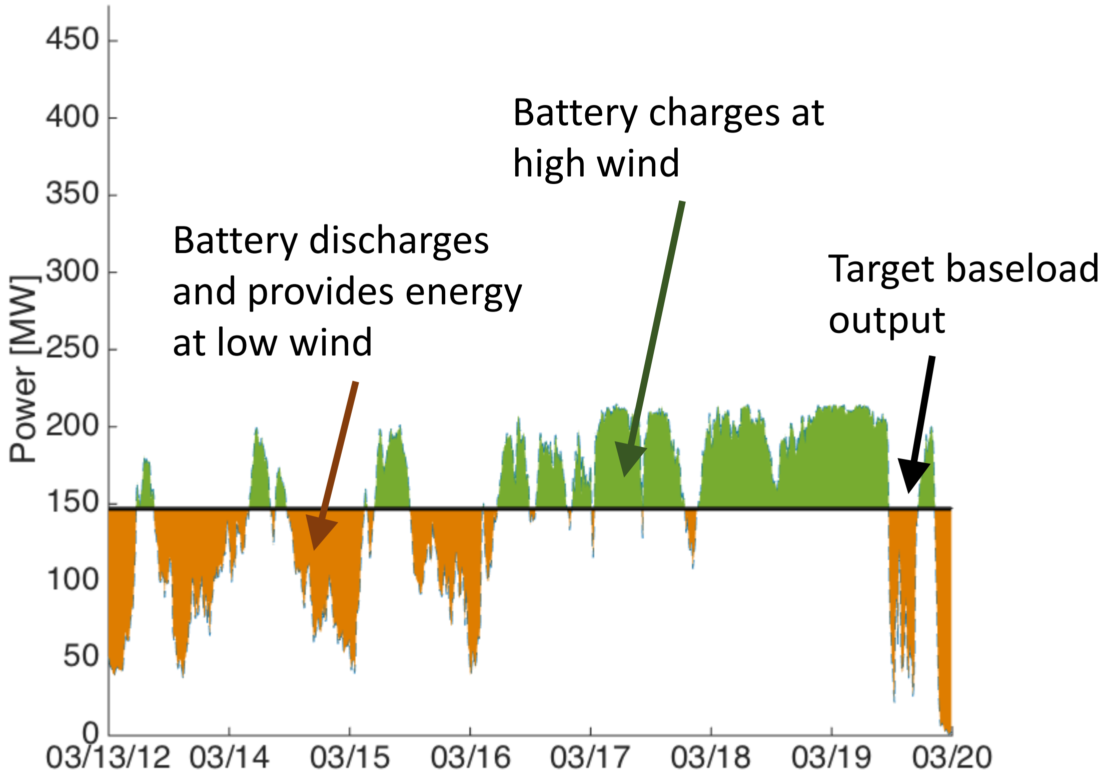
Parameters:

- 20-year, high-res US renewable generation data
- Baseload target shape
- Hourly storage dispatch simulations
- Four locations (IA, TX, AZ, MA)

Results:

- Combination of renewable + storage that **minimizes** LCOE (levelized cost of electricity) for each plant type

Example: Wind + Storage Baseload Replacement

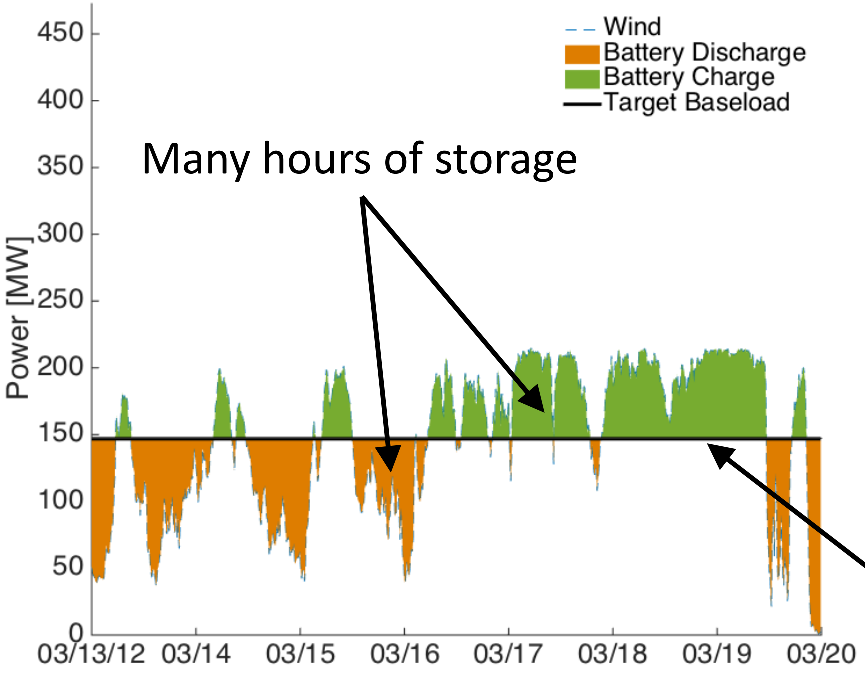


*J.M. Mueller, G. Pereira, M. Ferrara J. Trancik, Y.-M. Chiang, MIT 2017

Different Combinations of Wind and Storage Can Produce Same Output => Find Optimal One

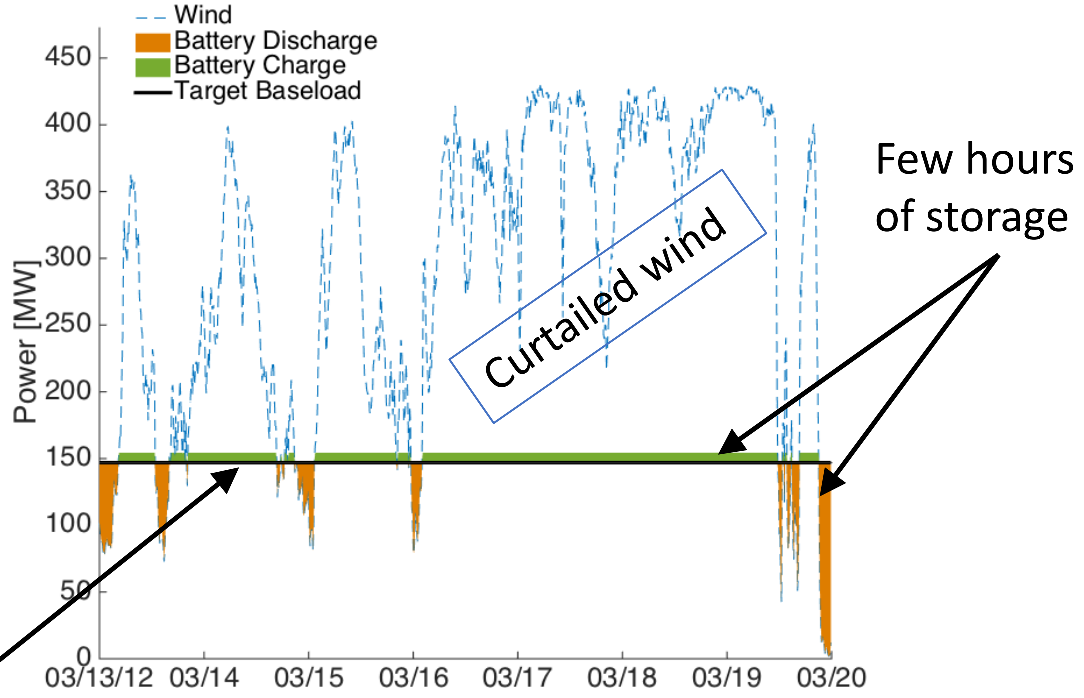
Low Storage Cost =>

Small wind + Big battery & No curtailment



High Storage Cost =>

Large wind + Small battery & Big curtailment

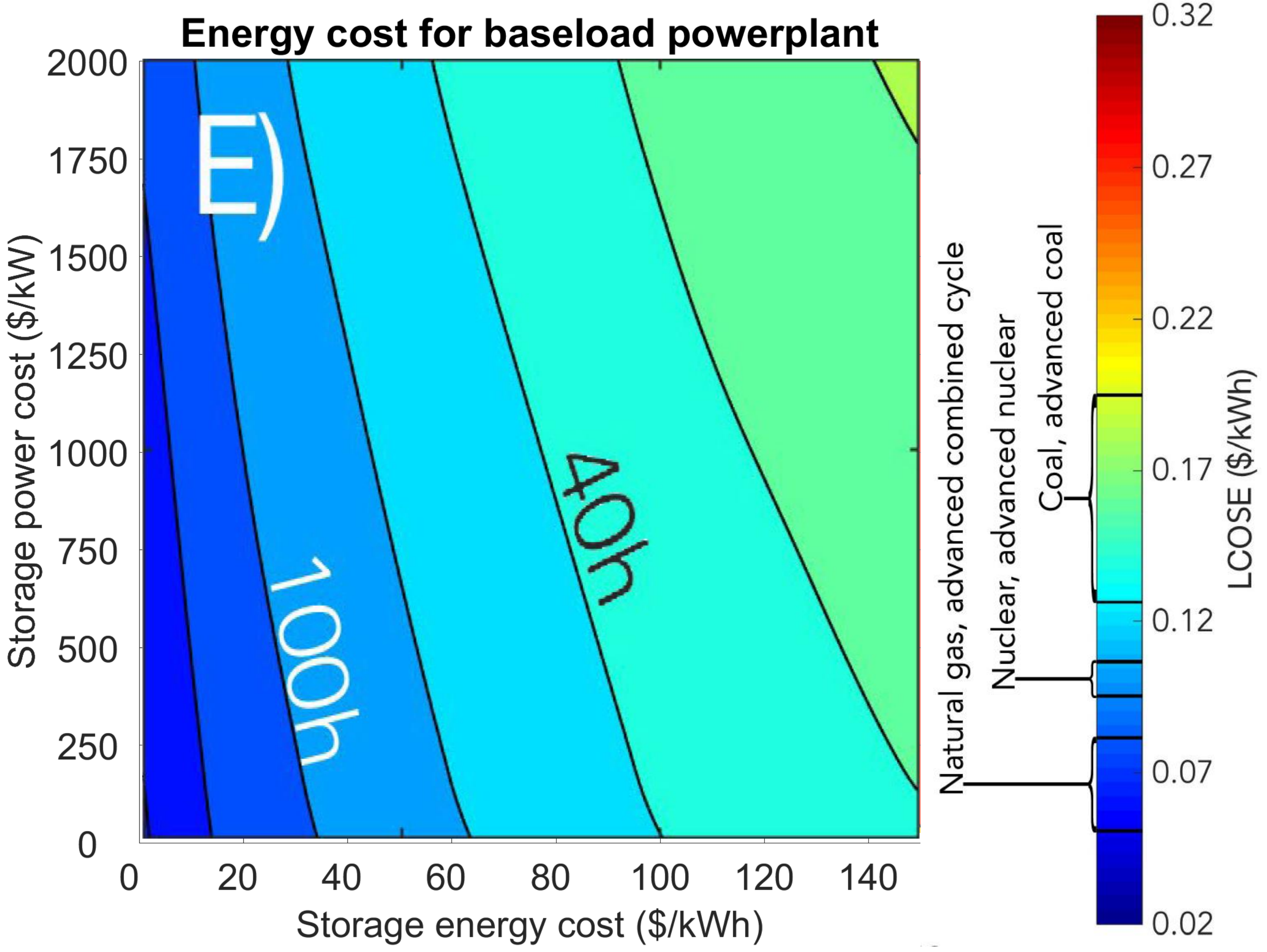


Same shape!!

Map of the Cost of Electricity from Iowa Wind + Storage Baseload Plant

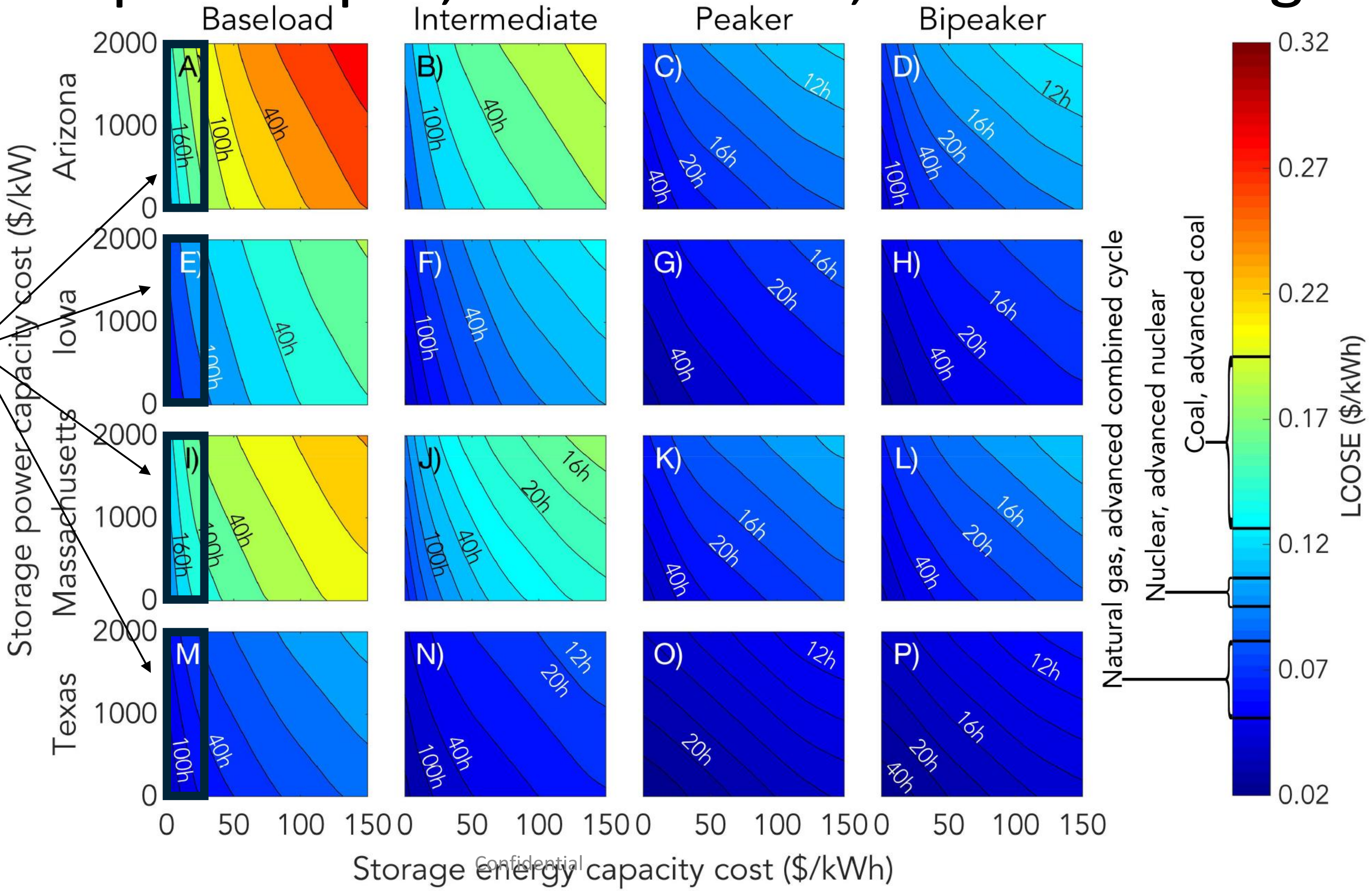
Condition Modeled:
- Iowa wind with ~50% capacity factor at total cost of ownership of $1,500/kW
- Baseline output

Outputs:
- Wind + Storage plant configurations that minimize LCOE
- LCOE over 20 years of output (Color map)
- Slope of contour lines gives maximum discharge rate in hours

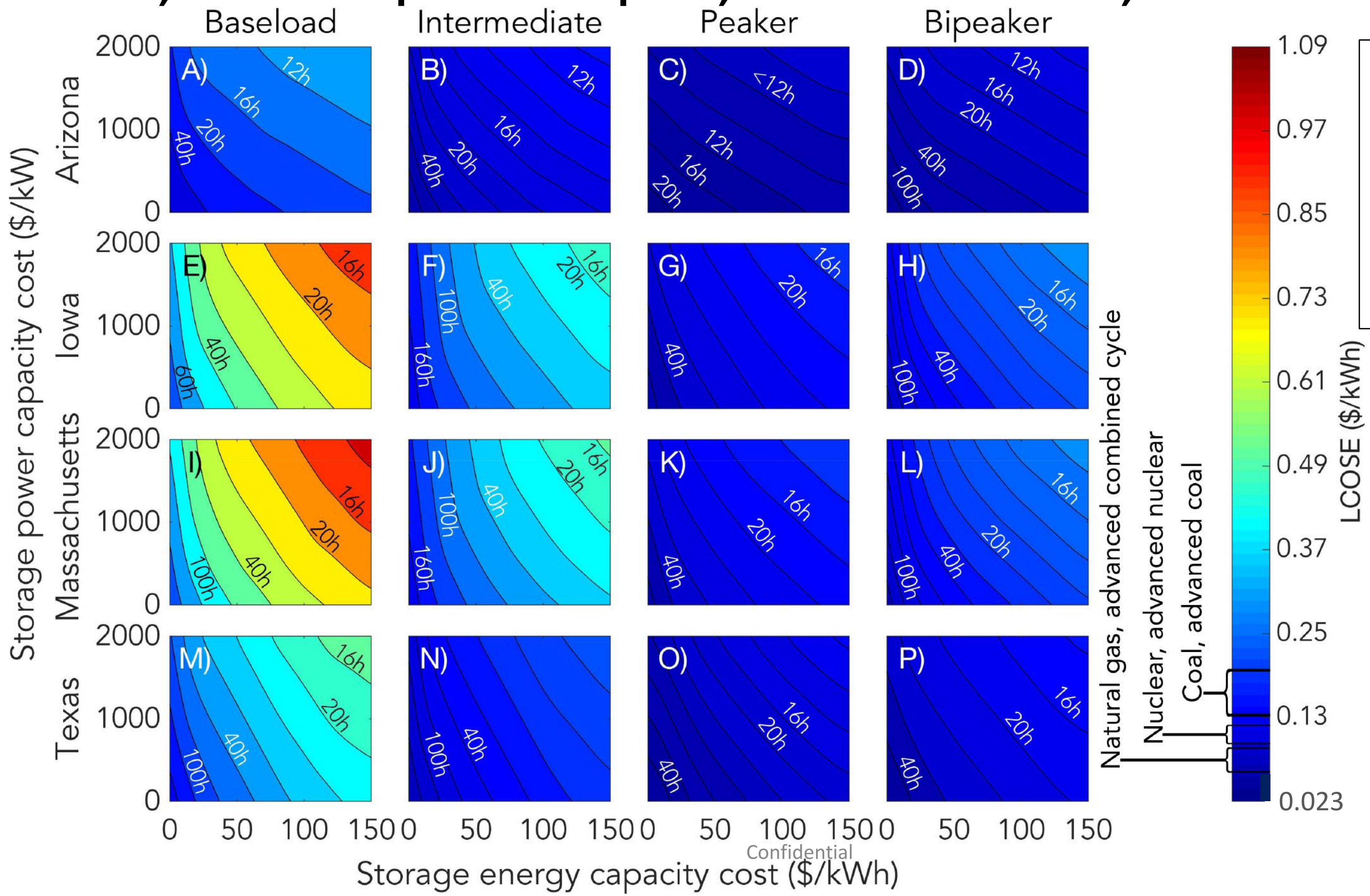


LCOE, All Output Shapes, All Locations, Wind + Storage

Ultra-low cost storage is favorable in all cases and indispensable to tackle the baseload challenge



LCOE, All Output Shapes, All Locations, Solar + Storage

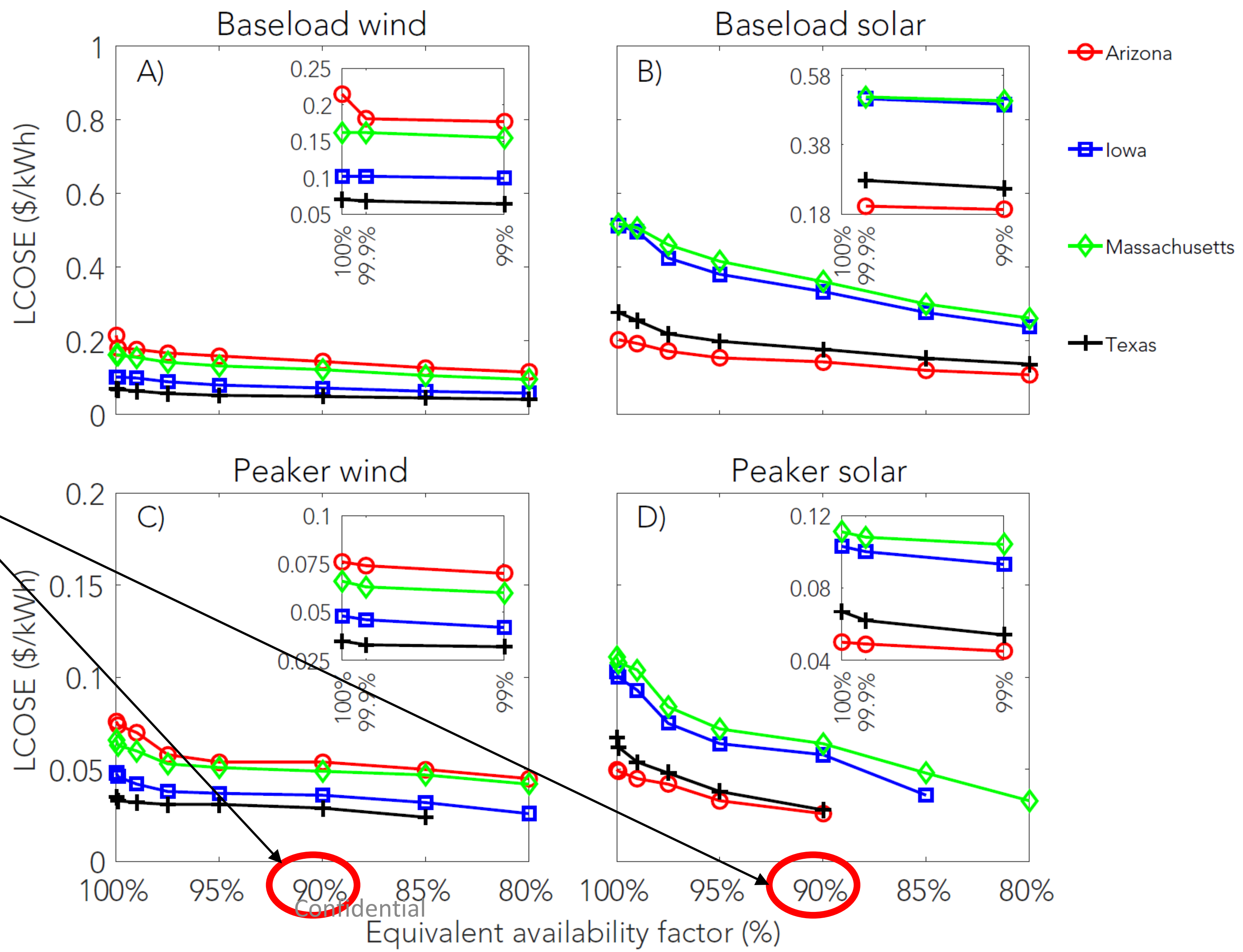


Solar is generally more expensive than wind for shapes with large energy requirements (capacity factors)

Relaxing Availability Requirement Reduces LCOE, Increases Competitiveness

Assumptions:
- Power cost $1,000/kW
- Energy cost $20/kWh
- RTE = 75%
- 20 years of hourly data

Best of class availability factor of conventional firm generation*

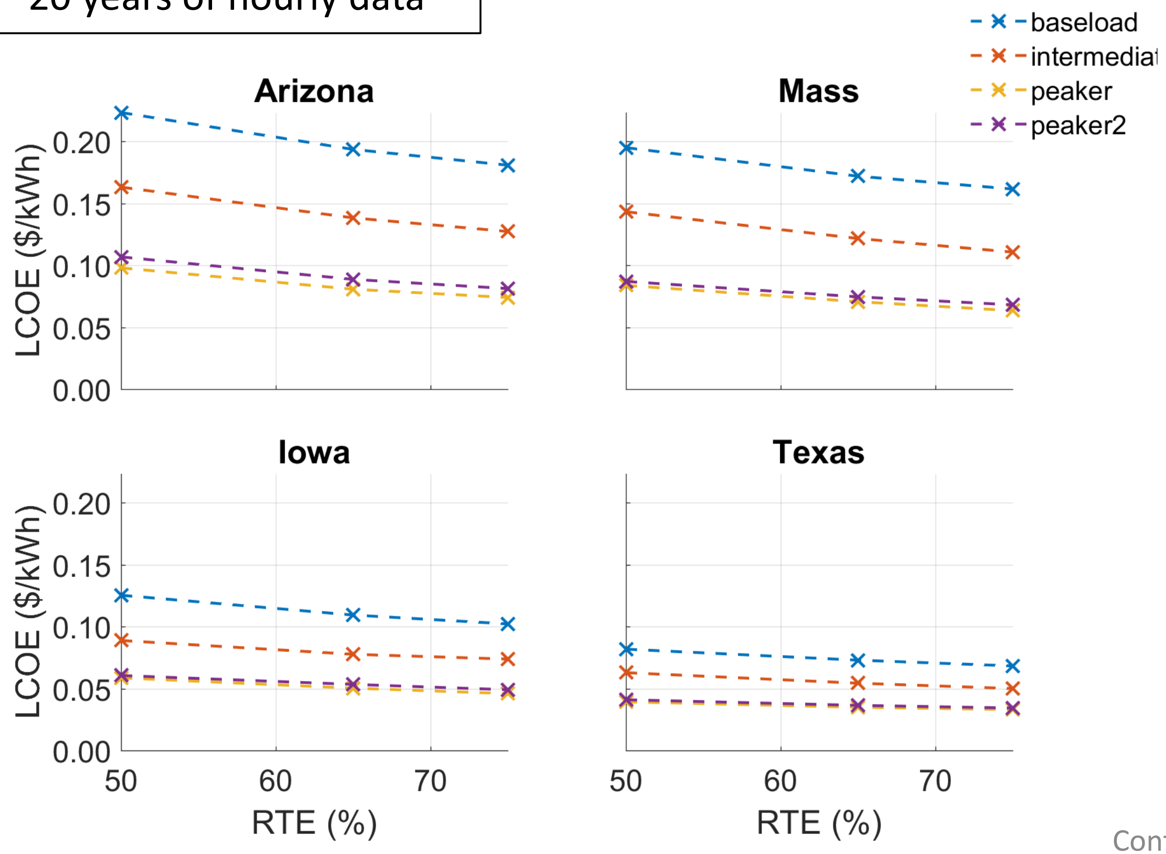


*Be aware of the difference between planned and unplanned outages and EAF!

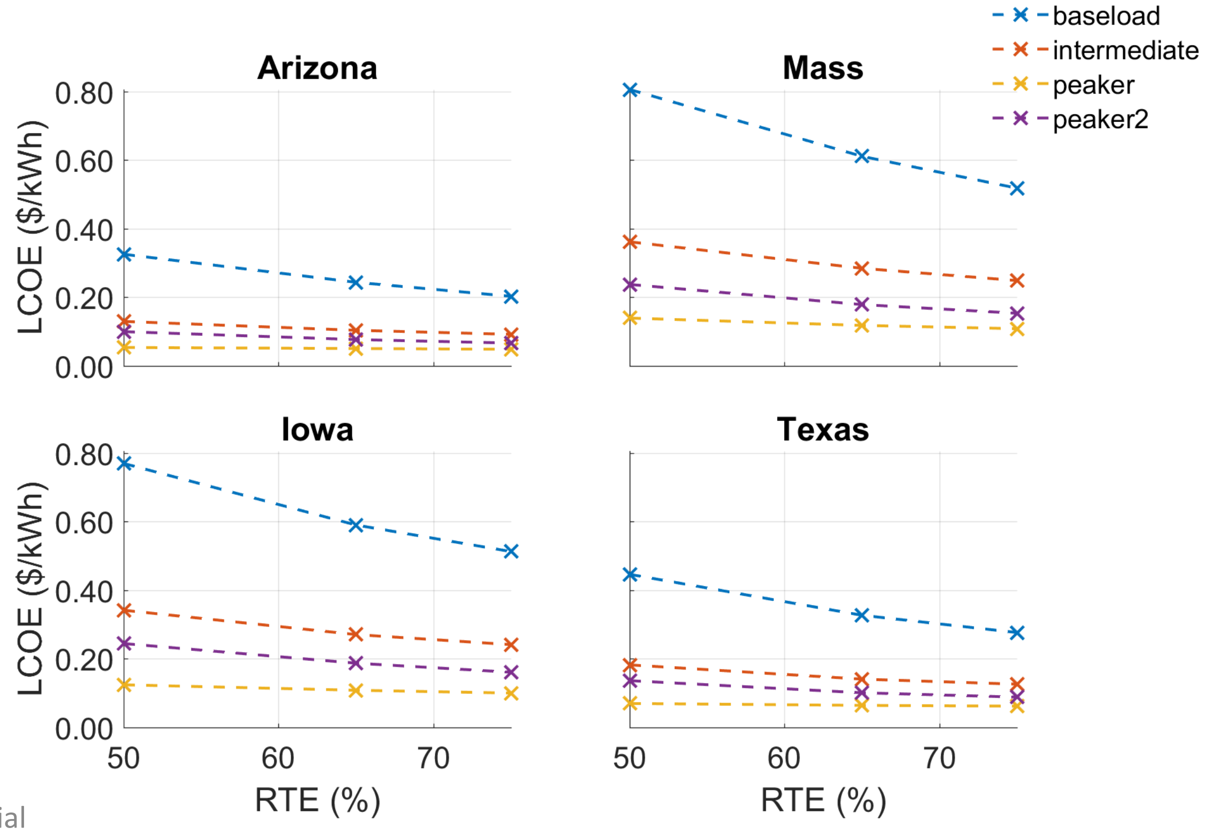
Sensitivity to Storage Round-trip Efficiency is Weak with Small $/kWh Rich Renewable Resource

Assumptions:
- Power cost $1,000/kW
- Energy cost $20/kWh
- EAF = 99%
- 20 years of hourly data

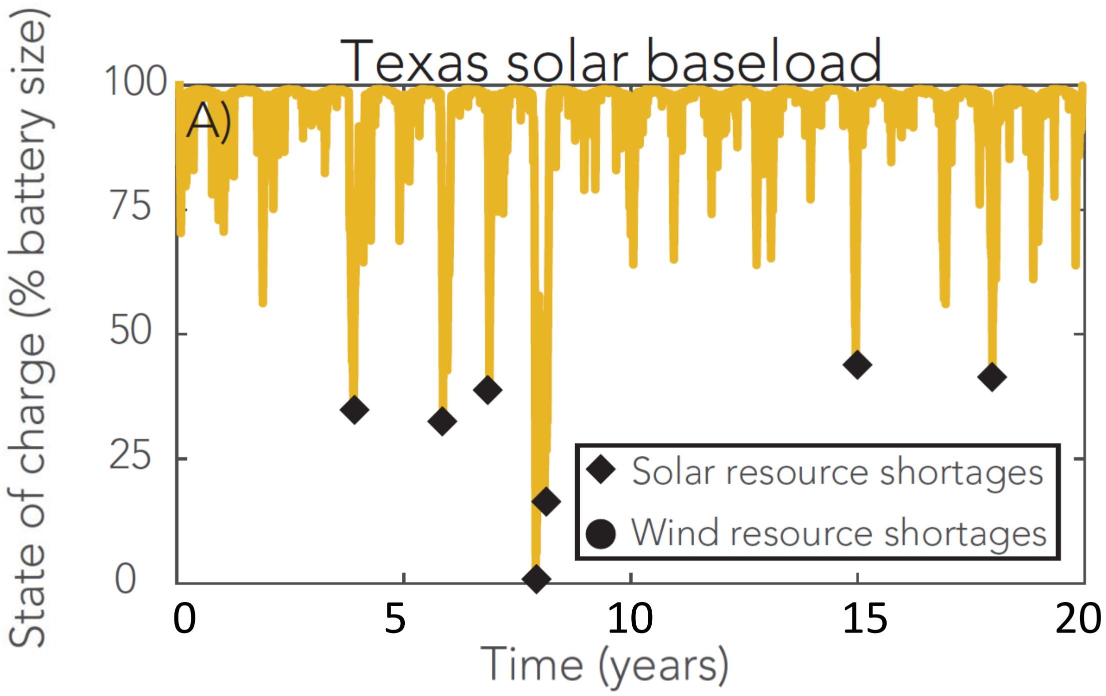
Wind

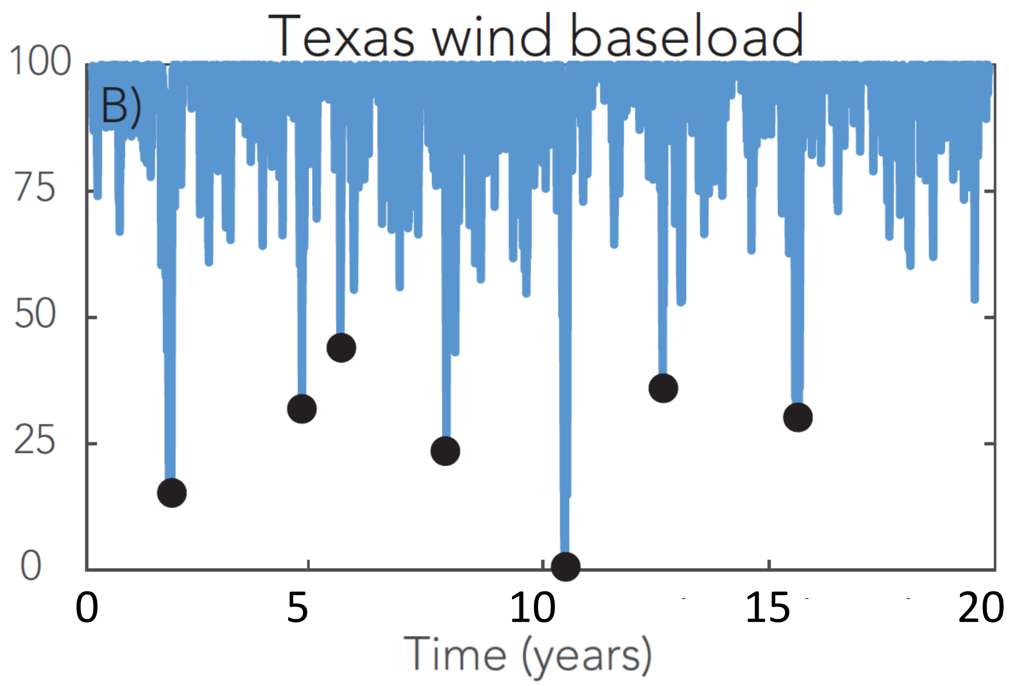


Solar



Deep Cycles are Rare. Battery is Mostly Held at High State of Charge



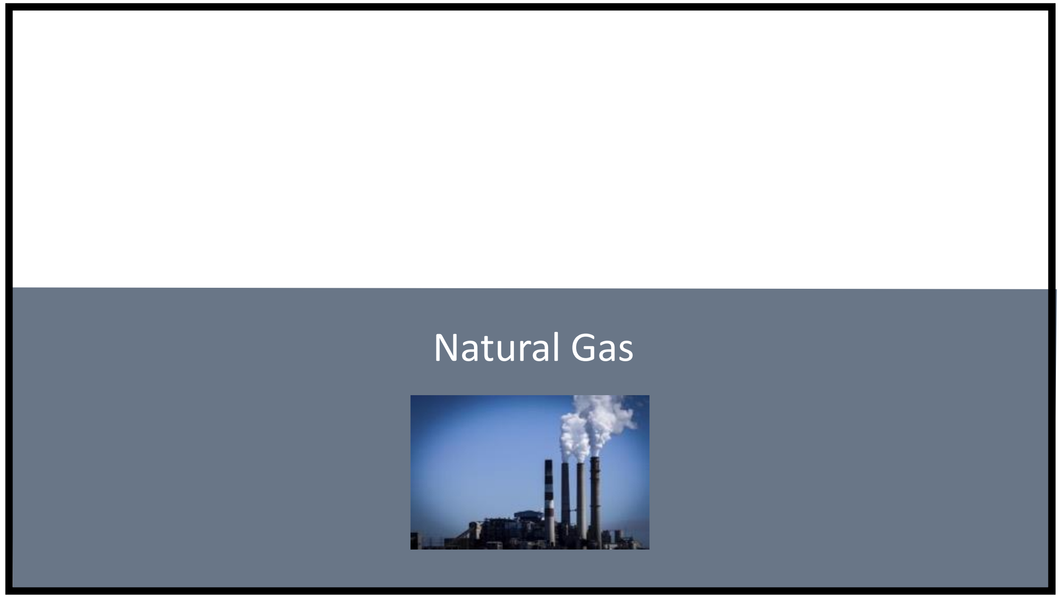


(Duty-cycle calculated at 99% availability factor. At lower values, utilization of storage increases substantially)

Baseload Power Plant Example

EAF = 90%

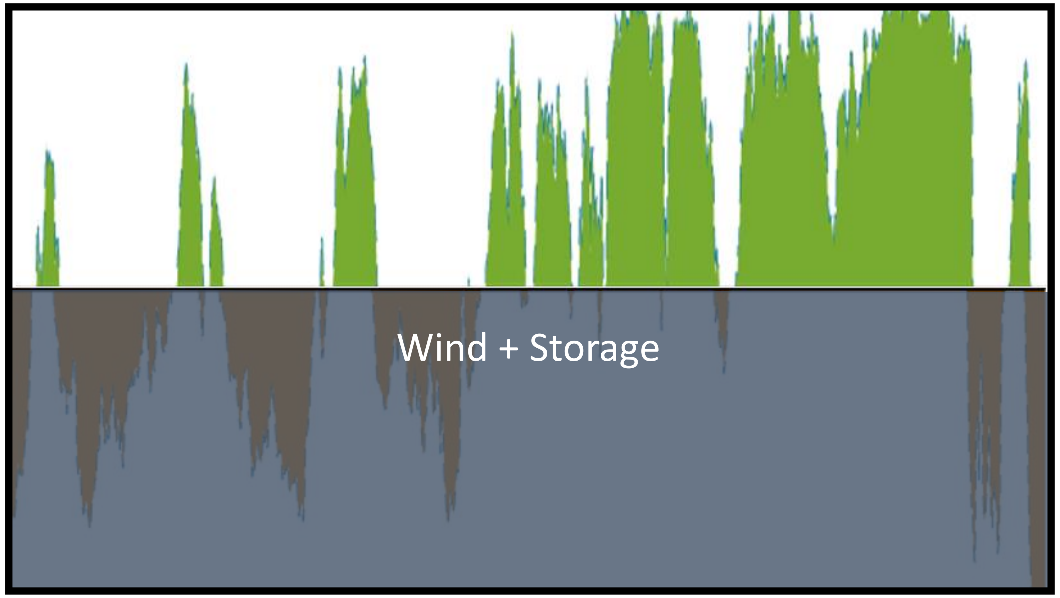
700 MW



Overnight	750MW	$1,230/kW	$920m
Fuel + O&M*	750MW		$2,600m
Baseload 20-years	**700MW**	**$5,030/kW**	**$3,520m**

* See appendix for assumptions

EAF = 90%, Iowa wind (50% capacity factor), RTE = 70%



Wind	1,500MW	$1,500/kW	$2,250m
Storage	660MW, 50h	$1,000/kW $20/kWh	$1,320m
Baseload 20-years	**700MW**	**$5,100/kW**	**$3,570m**
+Merchant	660GWh/y		

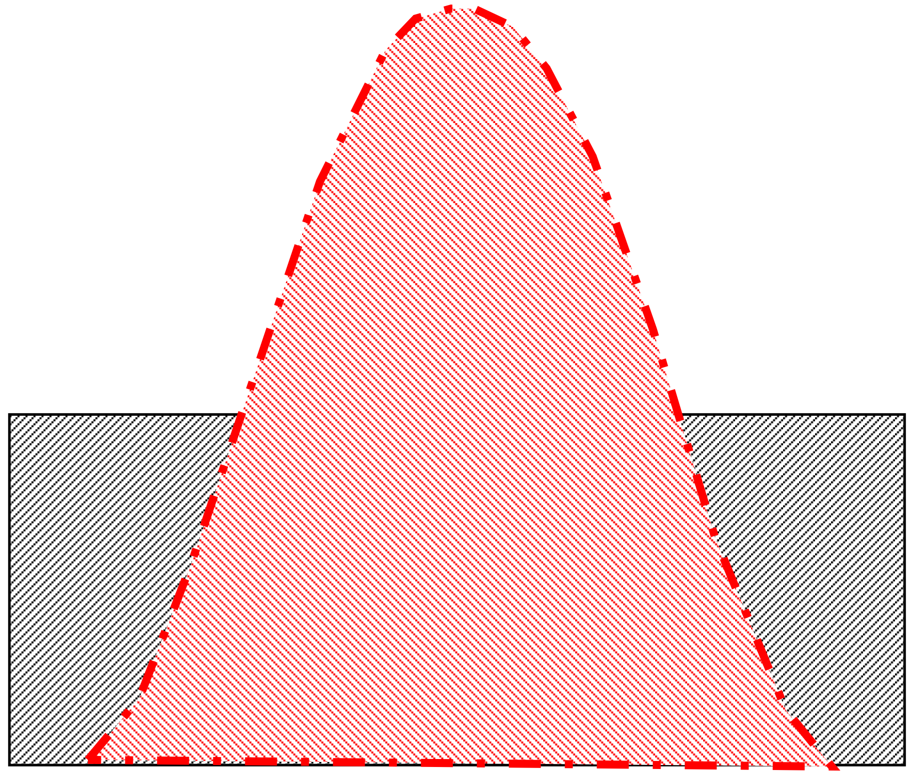
Summary

- Storage with low energy cost <\$20/kWh and long duration 100+ hours is required to produce reliable output cost-competitively with traditional generation.
- Sensitivity to power cost \$/kW and round-trip efficiency are weaker than to energy cost \$/kWh.
- Shelf-life is more important than cycle-life.

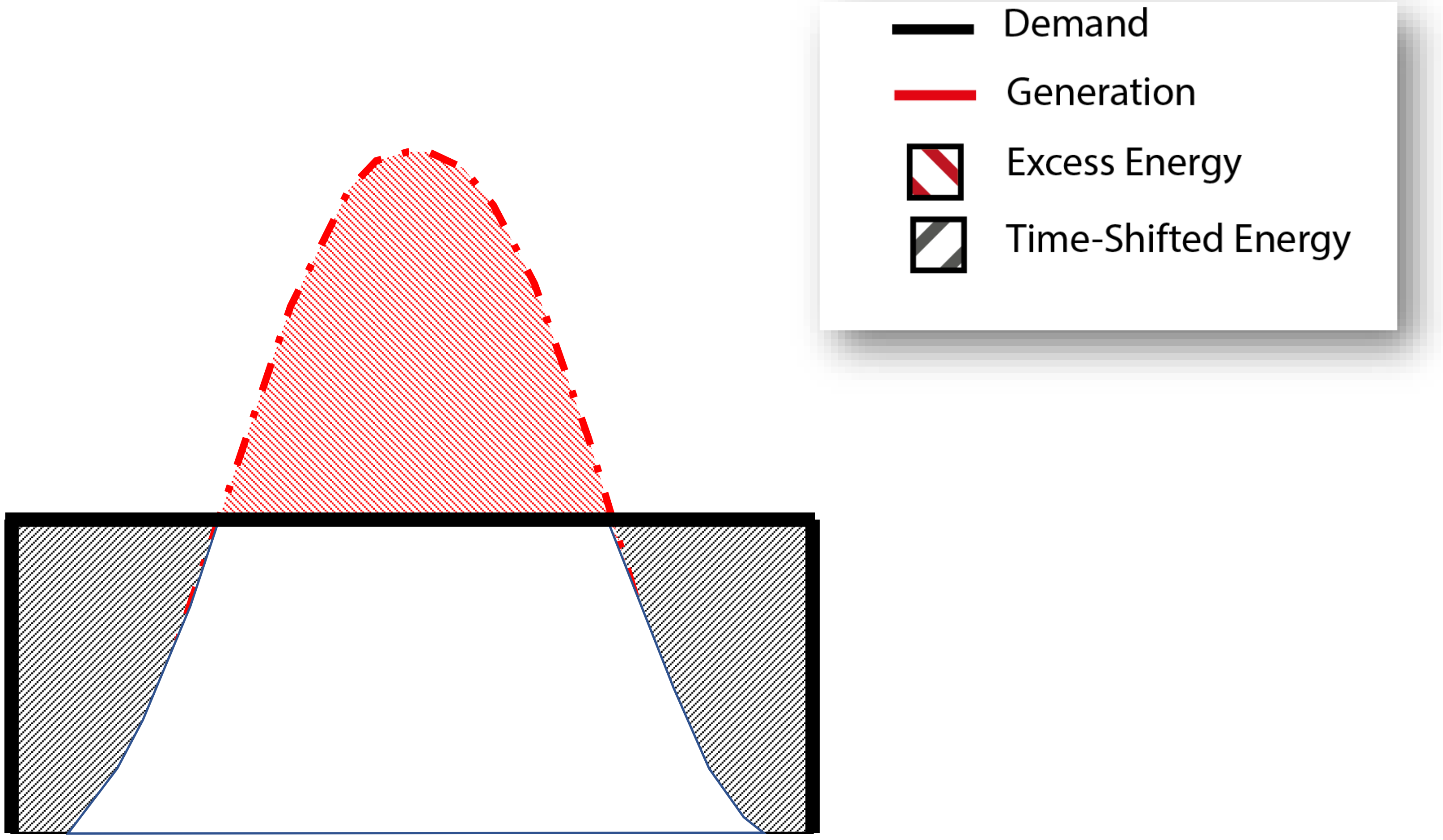
Appendix

Contents

Example Renewable Starting Point



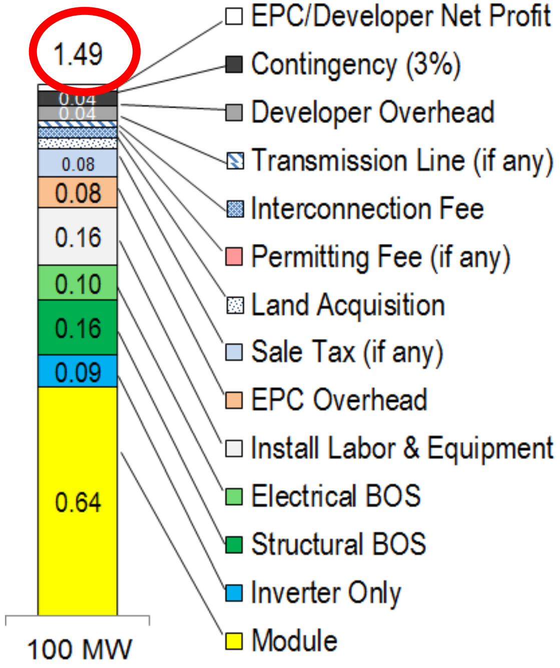
Addressable with Low Cost Storage



Fact Check: PV TCO

$1,000/kW overnight cost realistic

2016 Cost $1,500/kW



Room for improvement:

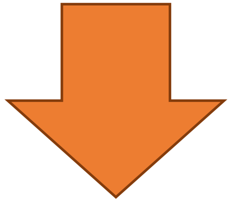
- **Modules today < $0.50/W**
- **Incremental improvements in efficiency**
- **Innovation in BOS expected (1,500 Vdc, mounting hardware, etc.)**

Industry expects $1,000/kW by 2020

$1,200/kW TCO realistic

TCO target = $1,200/kW

Overnight cost = $1,000/kW



Lifetime O&M < 20% TCO

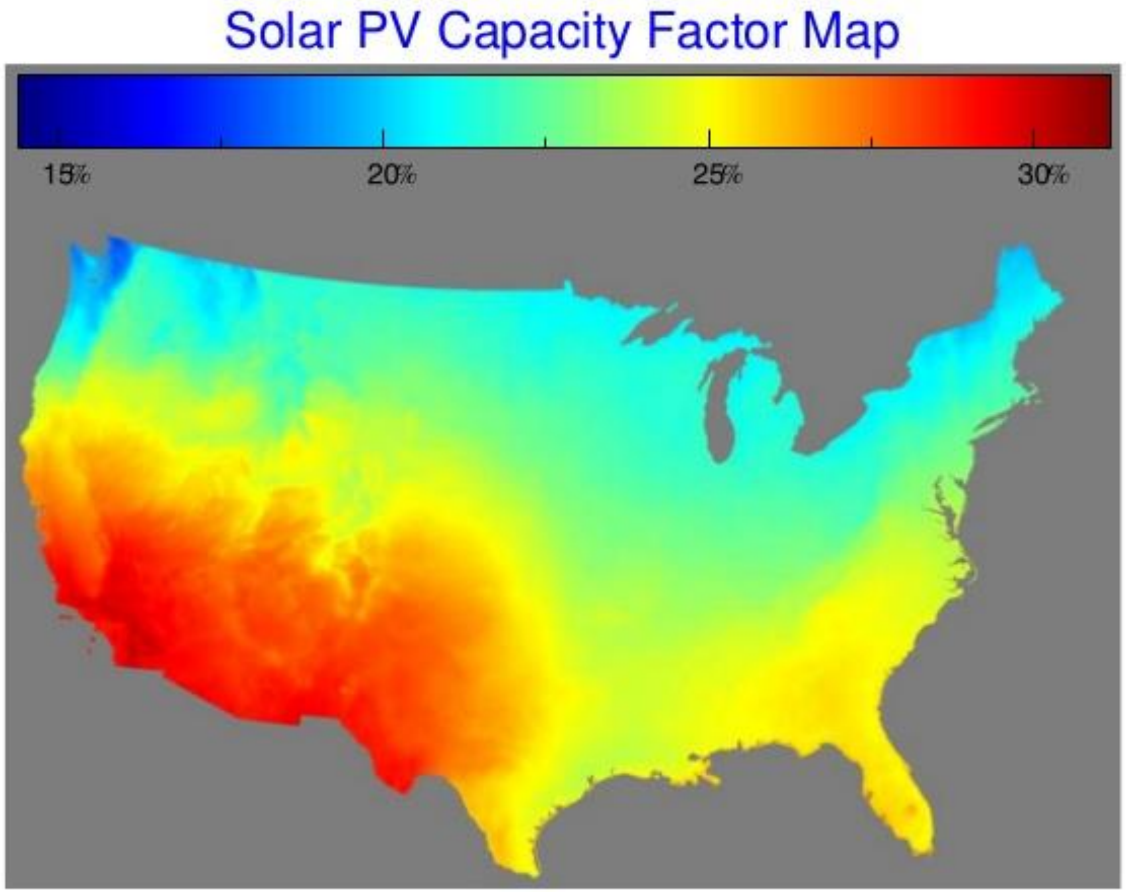
Best-of-class plants today

*https://www.nrel.gov/docs/fy16osti/67142.pdf

Fact Check: PV Capacity Factor

- NREL solar insolation map
- 18% module efficiency
- -14% losses, +20% AC/DC ratio
- +20% yield single-axis tracking
- <u>Capacity factors are realistic</u>

Arizona	Iowa	Mass	Texas
34.1%	25.5%	24.2%	31.0%



https://serc.carleton.edu/details/files/81036.html

Fact Check: Wind TCO

$1,200/kW overnight cost realistic

FIGURE 9: TOTAL INSTALLATION COSTS AND WEIGHTED AVERAGES OF COMMISSIONED AND PROPOSED WIND FARMS BY COUNTRY AND REGION, 2015

Source: IRENA Renewable Cost Database (2016)

$1,500/kW TCO realistic

TCO target = $1,500/kW

Overnight cost = $1,200/kW

Lifetime O&M < 20% TCO

Best-of-class plants today

Fact Check: Wind Capacity Factor

1. Is Iowa’s capacity factor of 50% realistic?
    - “Rotor scaling over the past few years has clearly begun to drive capacity factors higher. The average 2015 capacity factor among projects built in 2014 reached 41.2%, compared to an average of 31.2% among projects built from 2004–2011 and just 25.8% among projects built from 1998–2003.”*
    - Average 2015 rotor diameter ~100m, 160m already in the off-shore market.
2. Is LCOE ~ $20/MWh realistic?
    - “Focusing only on the Interior region, the PPA price decline has been more modest, from ~$55/MWh among contracts executed in 2009 to ~$20/MWh today. Today’s low PPA prices have been enabled by the combination of higher capacity factors, declining costs, and record-low interest rates documented elsewhere in this report.”*

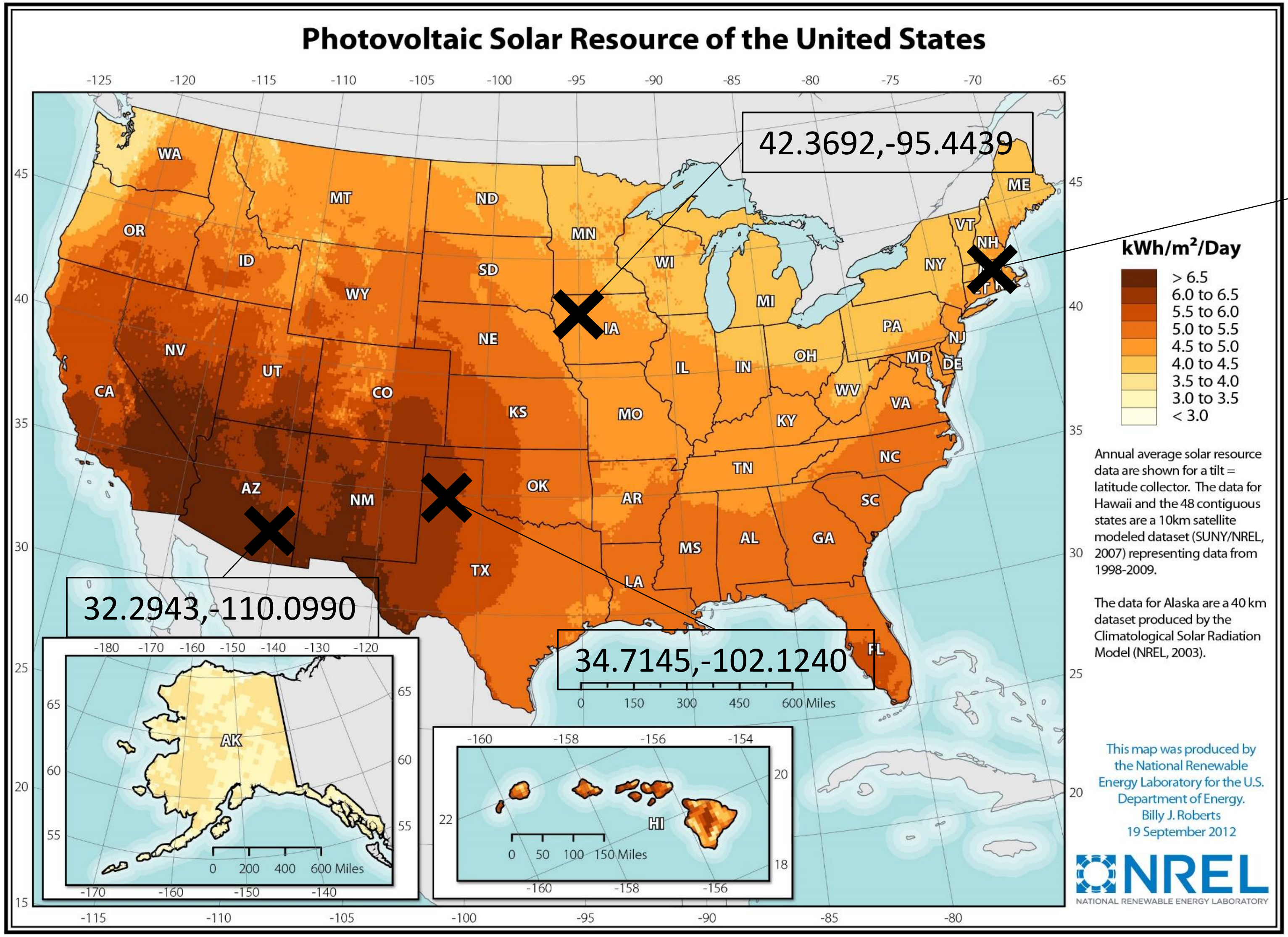
*https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf

Assumptions: PV

- PV module:
  - Mono-Si module, ~18% efficiency
- PV plant:
  - DC-AC losses 14%, DC/AC ratio 1.2
  - Single-axis tracking tilted at latitude, 0.4 ground coverage ratio
  - No downtime
- Cost assumptions:
  - Overnight cost < $1,000/kW
  - 20-year total cost of ownership $1,200/kW
- Calculated capacity factors:

Arizona	Iowa	Massachusetts	Texas
34.1%	25.5%	24.2%	31.0%

Four Locations Cover Diversity of Solar Resource



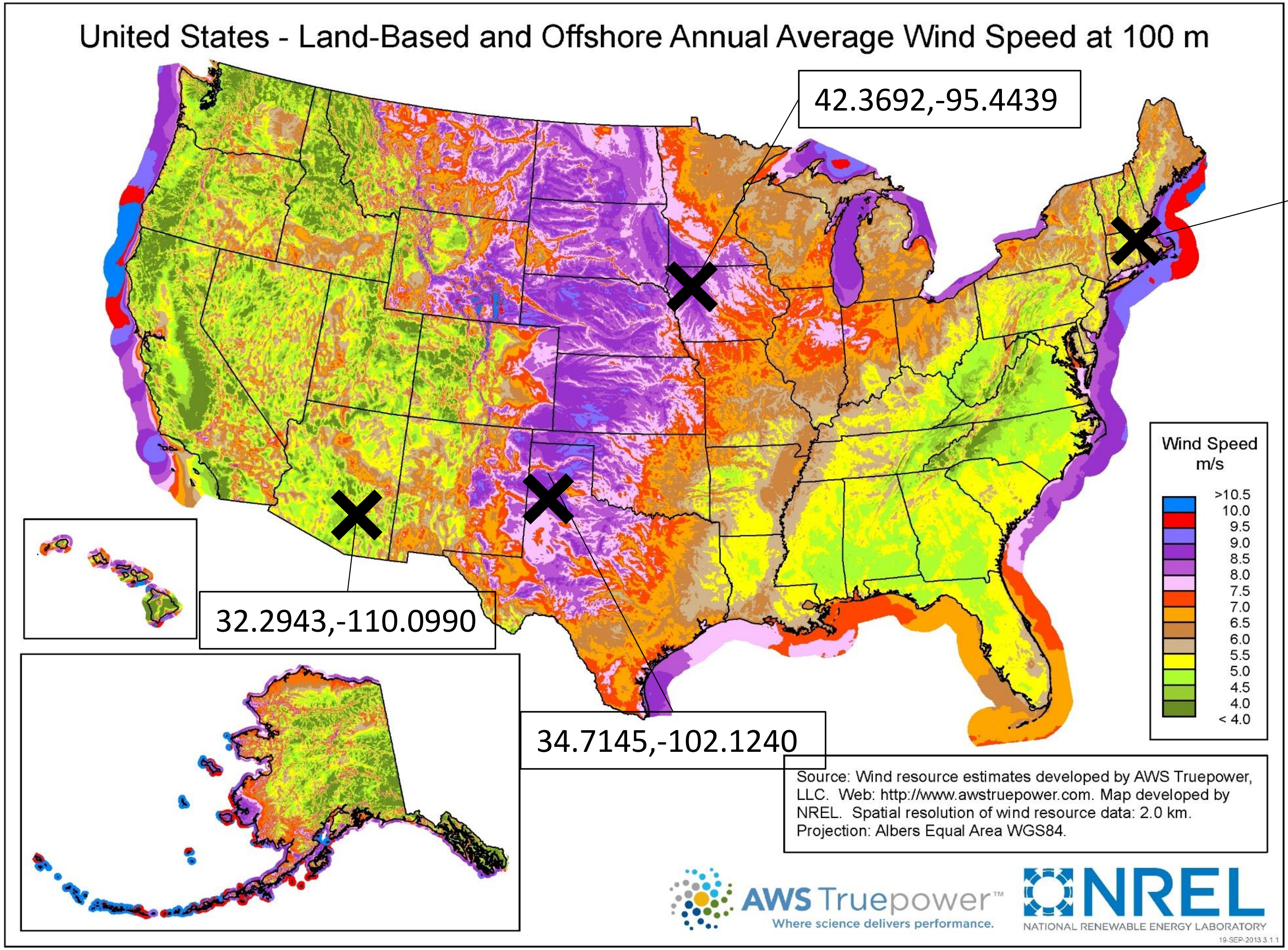
20-year, hourly resolution irradiance, temperature and wind from WRF model (AWS Truepower)

Assumptions: Wind

- Wind turbine:
  - Vestas 112 model turbine, 94m hub height
- Wind plant
  - No losses, no downtime
- Cost assumptions:
  - Overnight cost < $1200/kW
  - 20-year total cost of ownership = $1,500/kW
- Calculated capacity factors:

Arizona	Iowa	Massachusetts	Texas
38.6%	52.3%	40.7%	61.7%

Four Locations Cover Diversity of Wind Resource



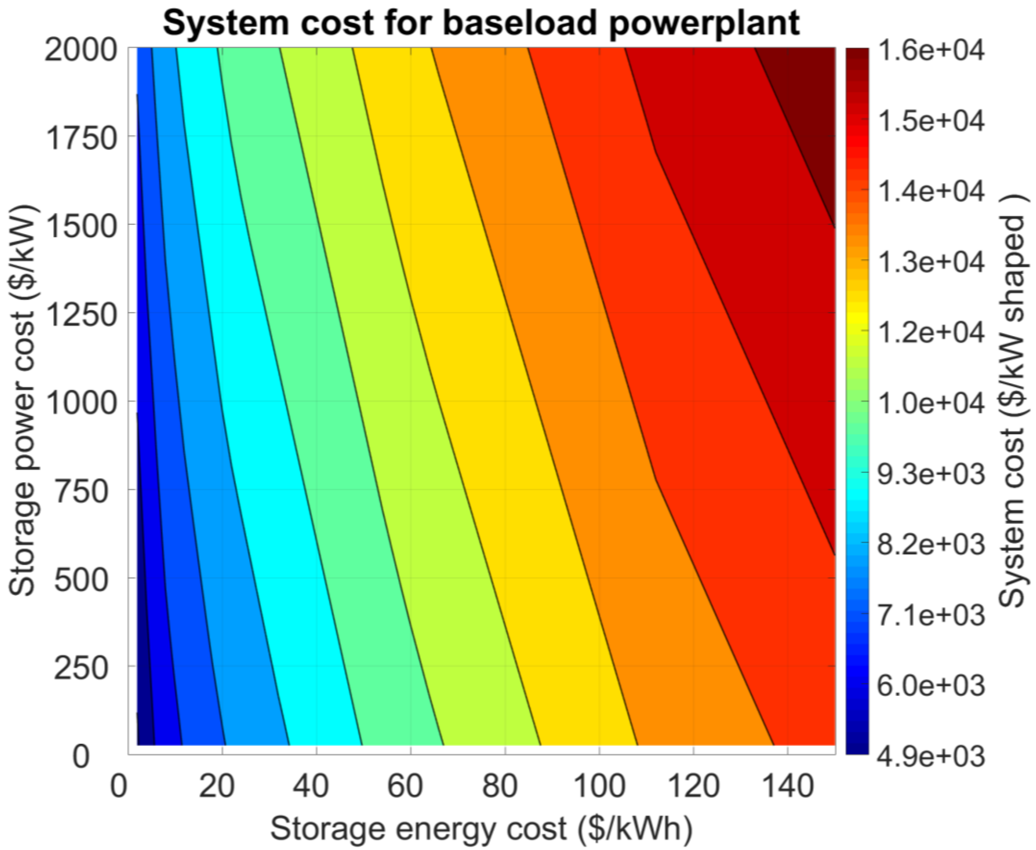
20-year, hourly resolution 100m altitude wind and air density from WRF model (AWS Truepower)

Storage Cost Convention

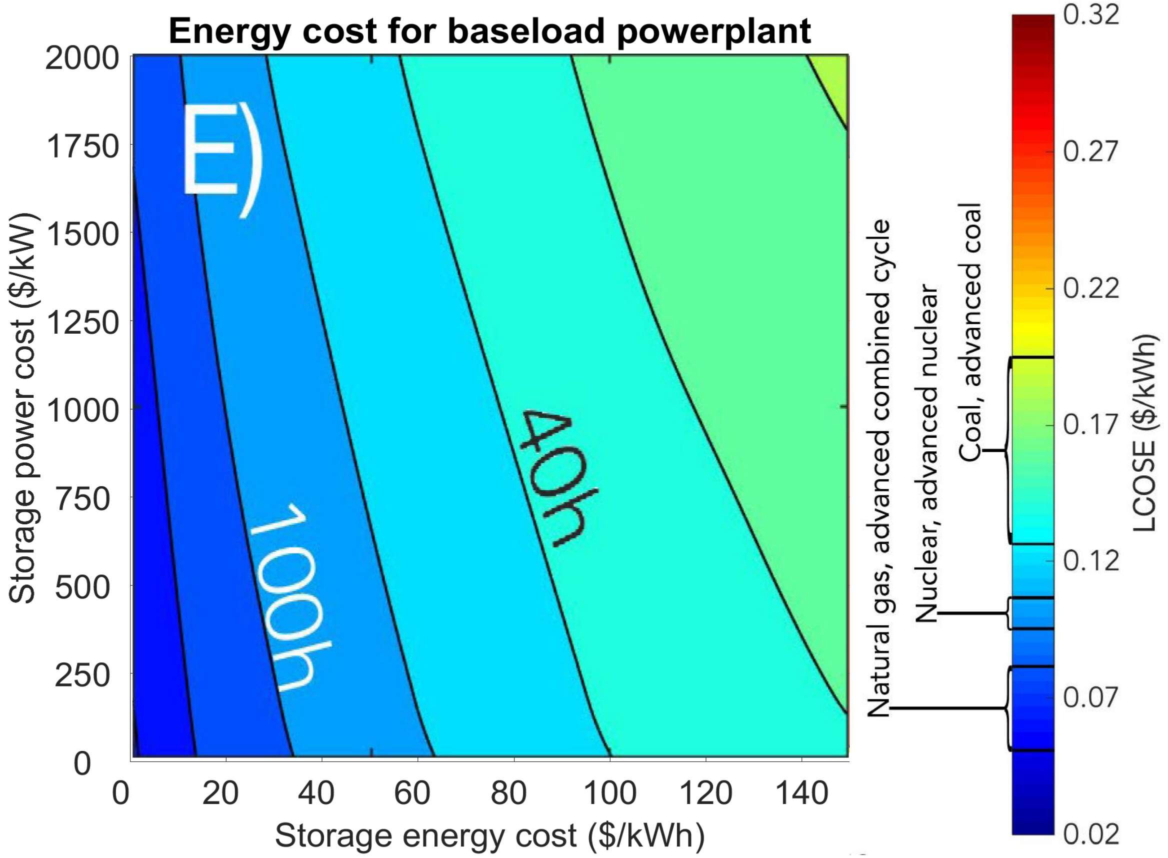
- Technologies w/o intrinsic C-rate constraints (e.g. flow battery, pumped hydro):
  - Energy cost ⬄ Tanks, working fluids, land, EPC (as it scales with battery rated energy), etc.
  - Power cost ⬄ Turbines, electrochemical stack, pumps, pipes, EPC (as it scales with battery rated power), HVAC, power conversion electronics, etc.
- For technologies w/ intrinsic C-rate constraints (e.g. Li-ion):
  - Energy cost ⬄ Racks, enclosure, land, EPC (energy), etc.
  - Power cost ⬄ EPC (power), HVAC, power conversion electronics, etc.

Overall, System Cost and LCOE Increase Primarily with Storage $/kWh Cost

Storage $/kWh cost is the primary driver of system cost

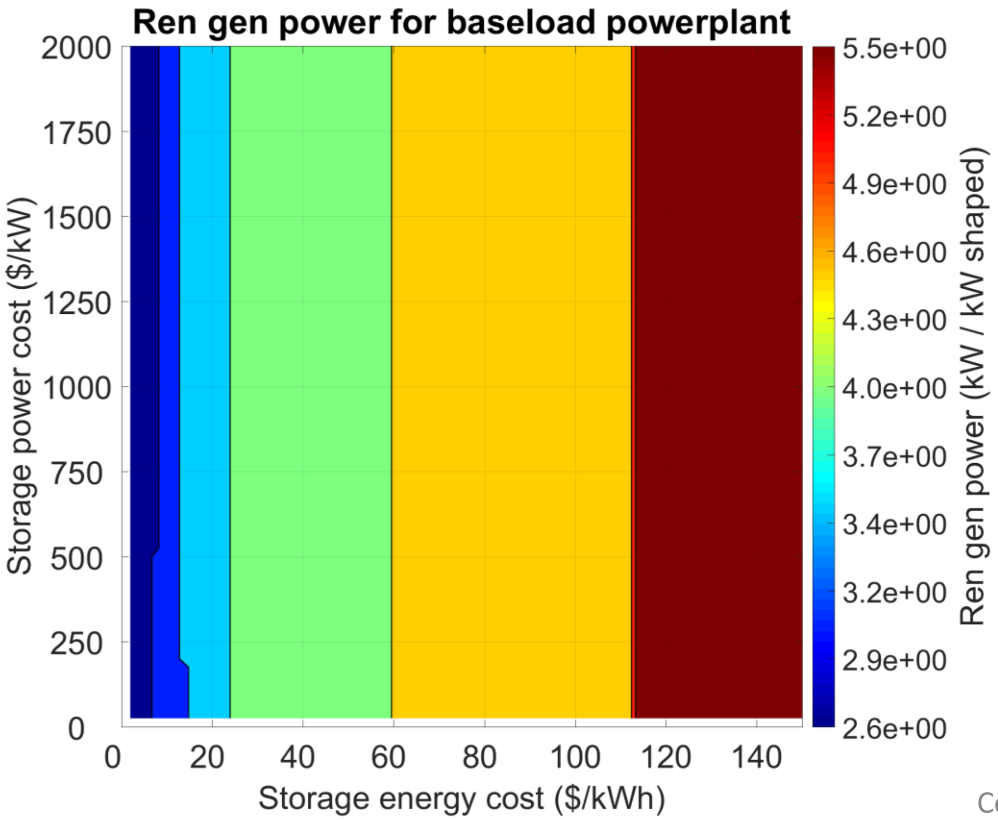


Storage $/kWh cost is the primary driver of baseload LCOE

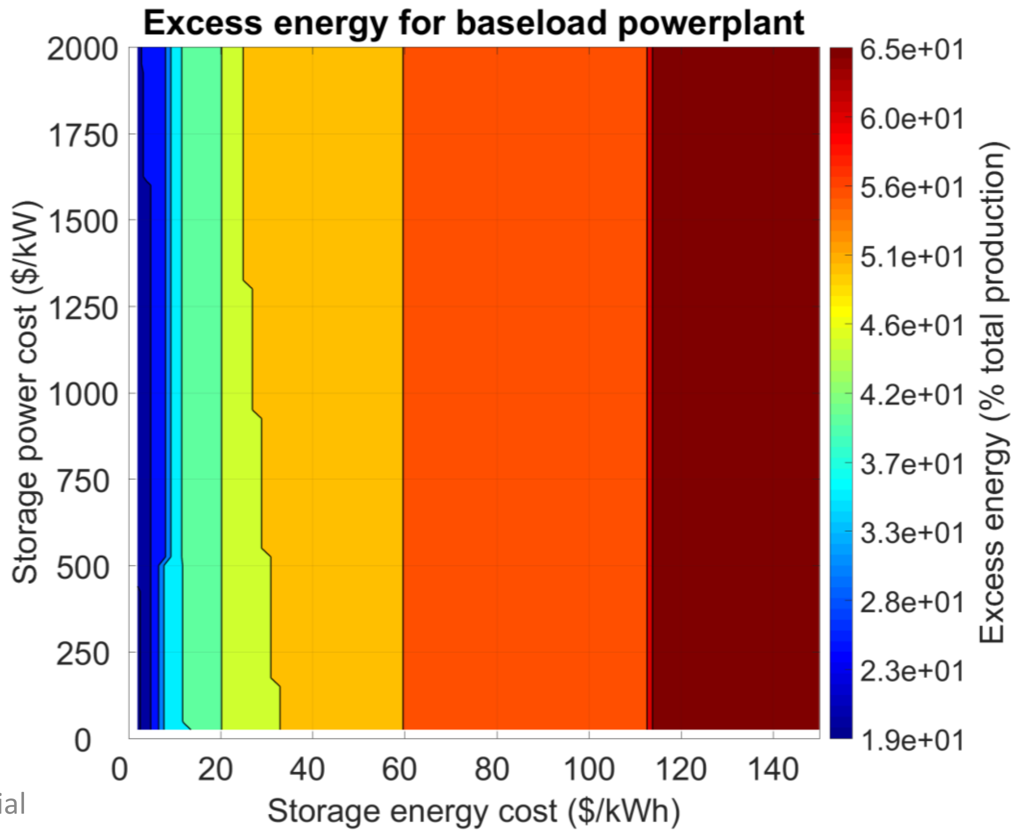


Renewable Installed Power and Curtailment Decrease Substantially with Storage $/kWh Cost

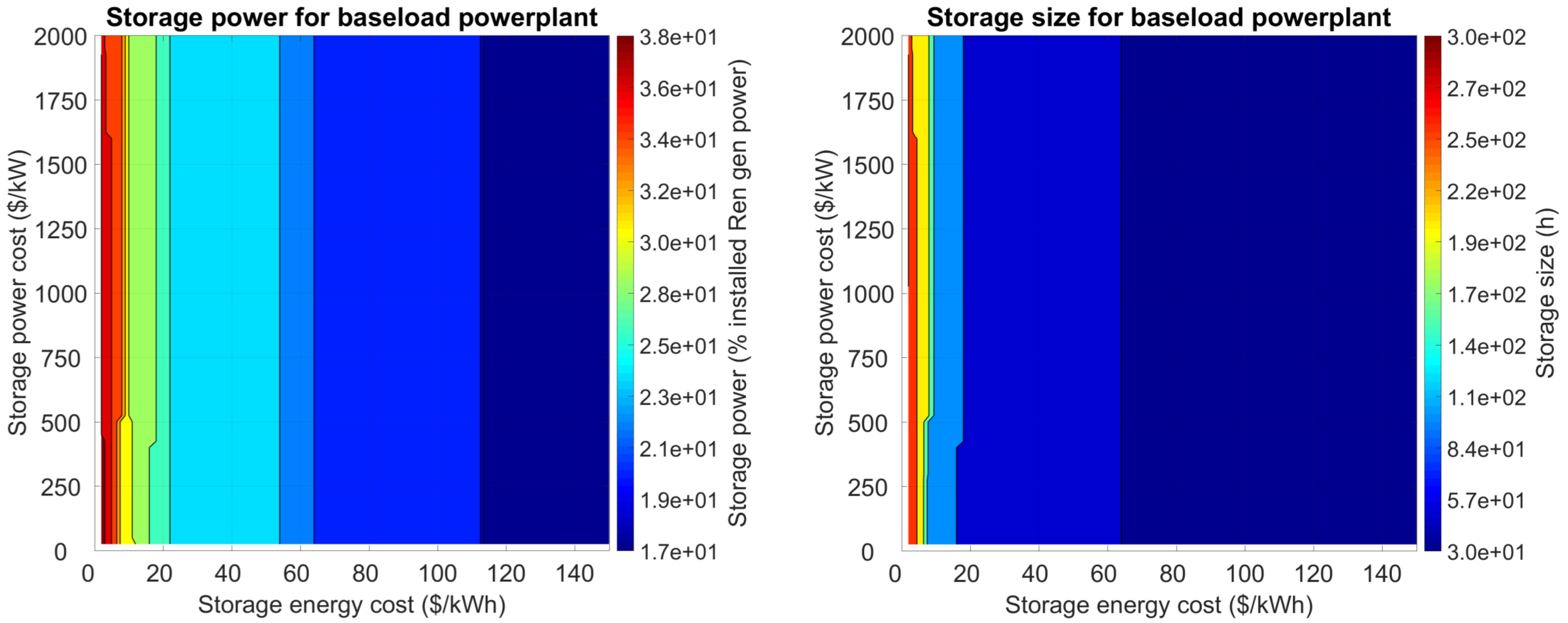
The most cost-effective way to meet output requirements at high storage energy cost is renewable oversizing



As a consequence, the amount of curtailed renewable energy increases substantially



The most cost-effective way to meet output requirements at low storage energy cost is a large storage system

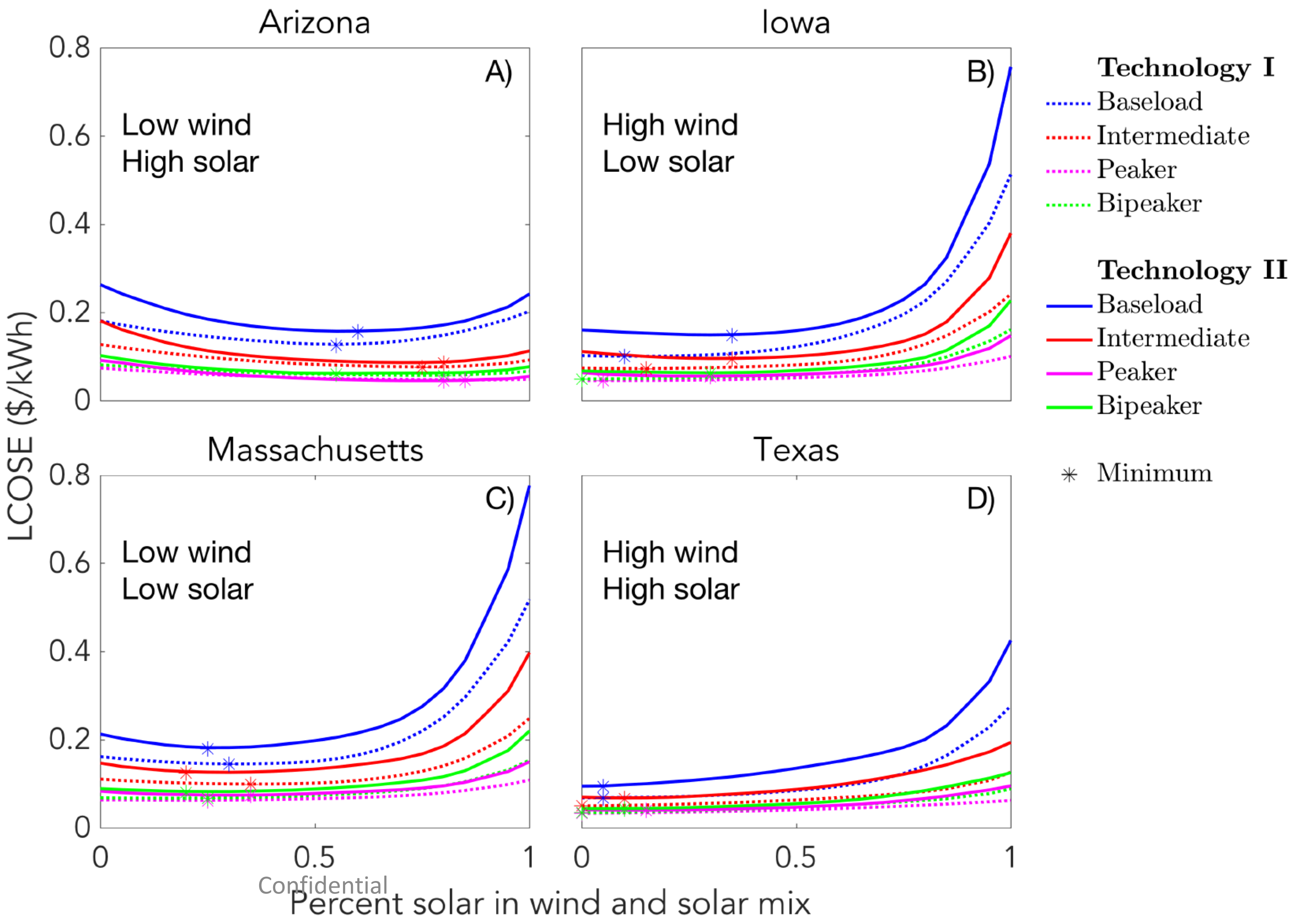


Wind Tends to Be the Preferred Resource Except in Areas with Low Capacity Factor

Technology I:
- Power cost $1,000/kW
- Energy cost $20/kWh

Technology II:
- Power cost $50/kW
- Energy cost $150/kWh

General:
- RTE = 75%
- EAF = 99%



Levelized Cost of Electricity Captures System Economics and Trade-offs for Baseload Output

$$LCOE = \frac{P_{RE} * TCO_{RE} + P_{ESS} * TCO_{ESS\_kW} + E_{ESS} * TCO_{ESS\_kWh}}{Baseload\ Total\ Output\ Energy}\ \frac{\$}{kWh}$$

Where:

$P_{RE} \stackrel{\text{def}}{=} Power\ of\ Renewable\ Generator\ (Wind, Solar)\ [kW]$

$E_{ESS} \stackrel{\text{def}}{=} Energy\ of\ Battery\ [kWh]$

$P_{ESS} \stackrel{\text{def}}{=} Power\ of\ Battery\ [kW]$

$TCO \stackrel{\text{def}}{=} Total\ Cost\ of\ Ownership = Capex + Opex\ [\$]$

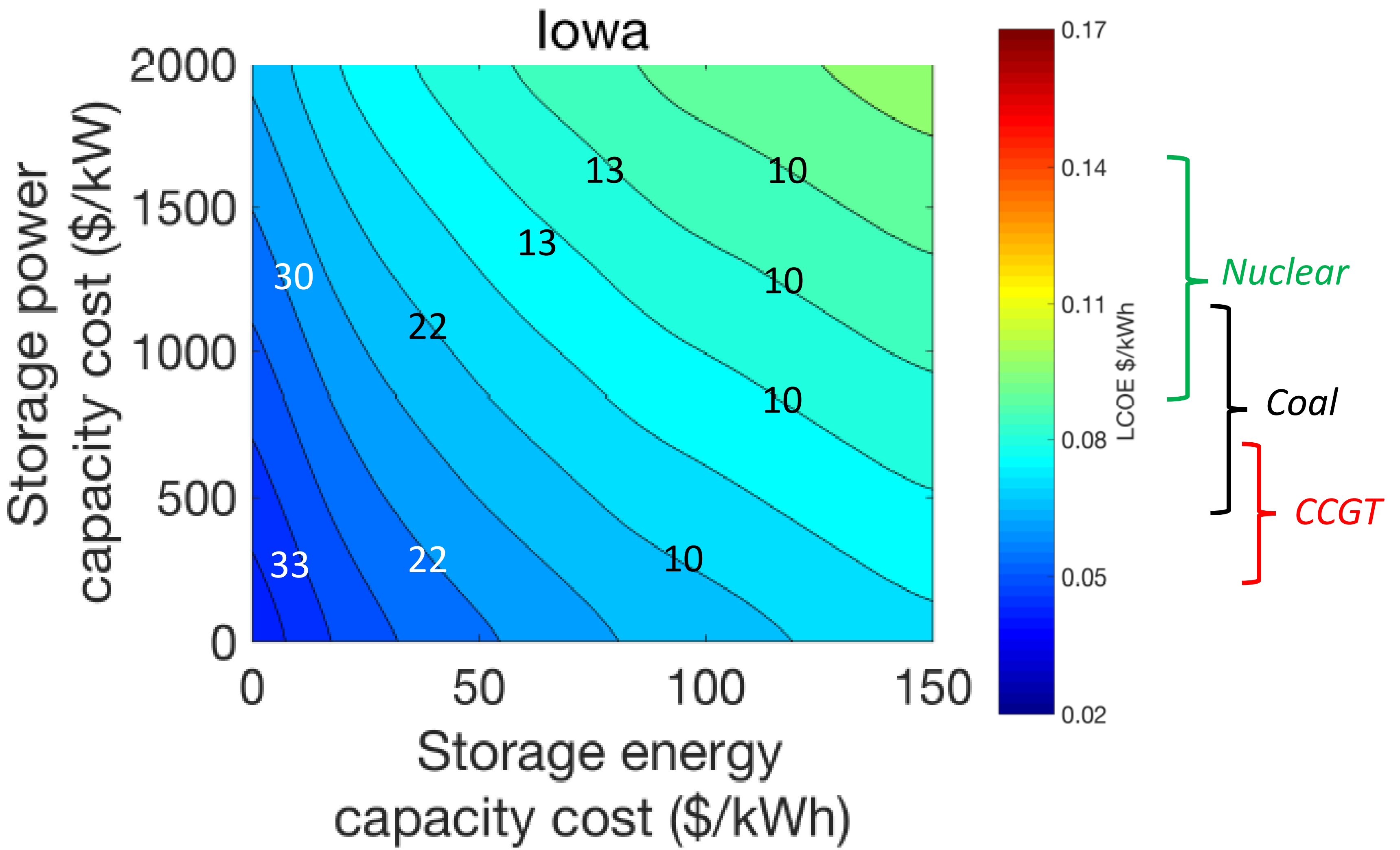
Map of the Cost of Electricity from a Wind + Storage Baseload Plant

Condition Modeled:

- Iowa wind with ~50% capacity factor at total cost of ownership of $1,500/kW
- 24 hour baseload output at 90% annual availability

Outputs:

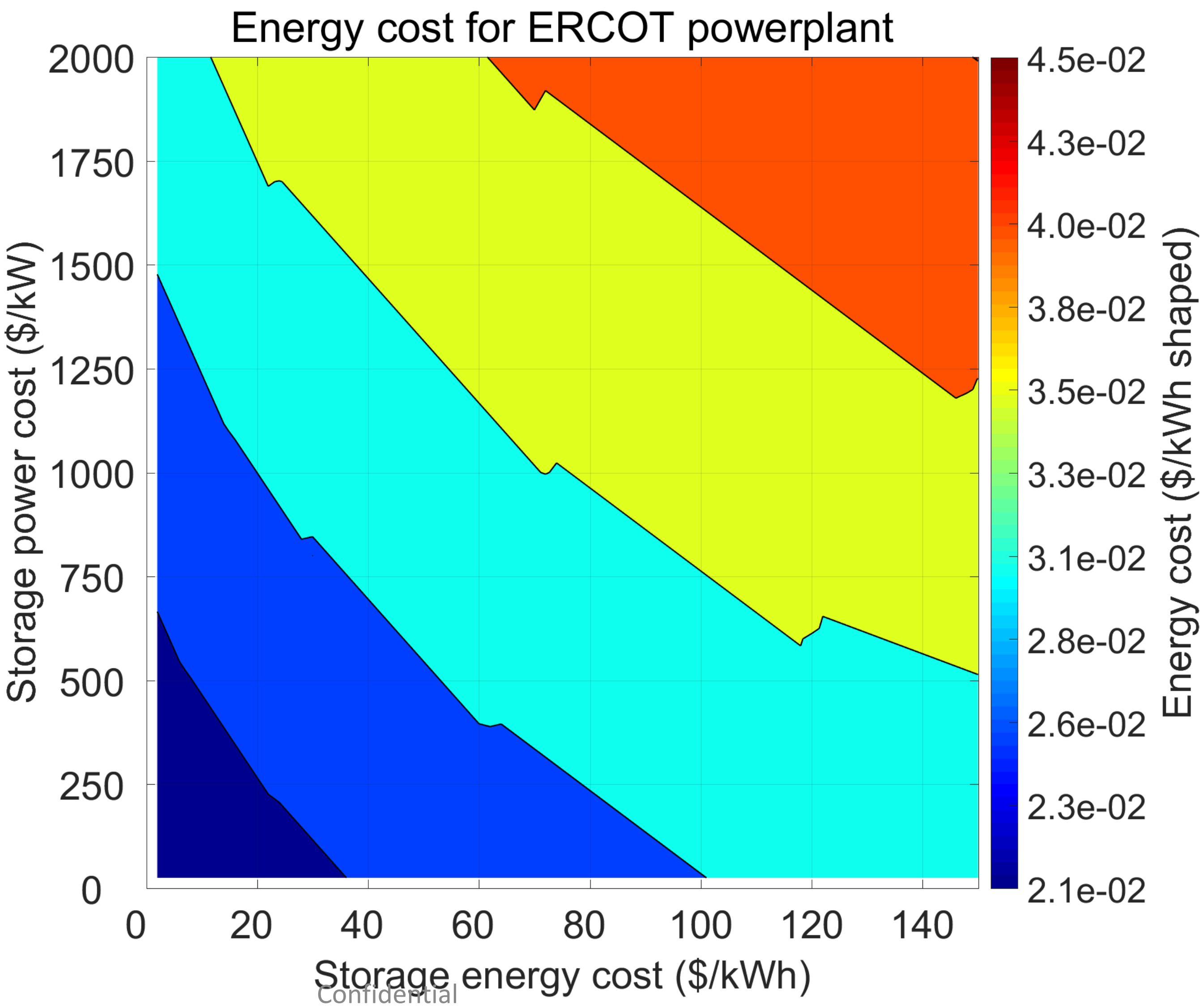
- Wind + Storage plant configurations that minimize LCOE
- LCOE over 20 years of output (Color map)
- Slope of contour lines gives maximum discharge rate in hours



Map of the Cost of Electricity from a Wind + ERCOT Load Profile

Condition Modeled:
- Texas wind with ~60% capacity factor at total cost of ownership of $1,500/kW
- ERCOT 2016 hourly load output at 90% annual availability
- Storage RTE of 60%

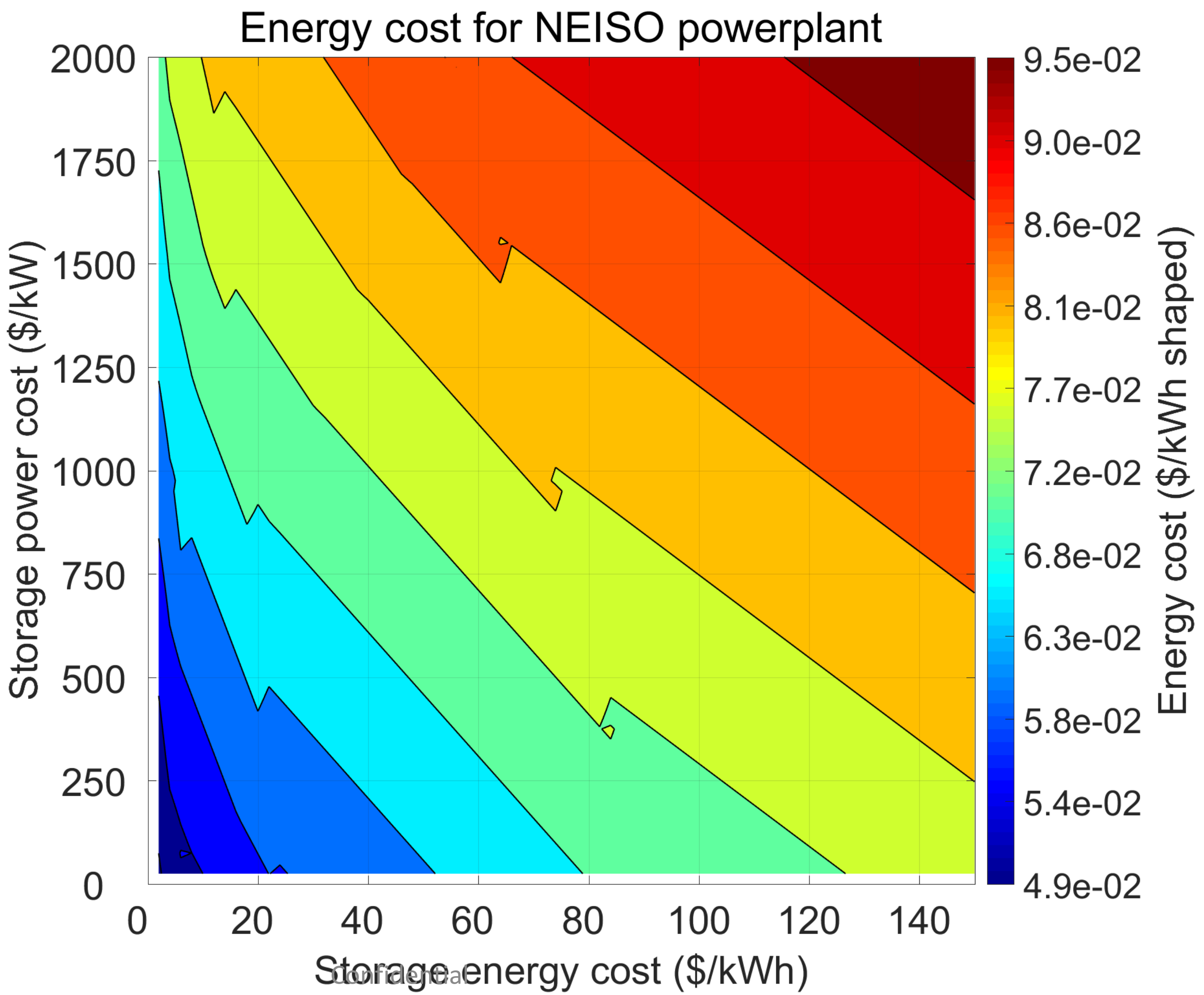
Outputs:
- Wind + Storage plant configurations that minimize LCOE
- LCOE over 20 years of output (Color map)
- Slope of contour lines gives maximum discharge rate in hours



Map of the Cost of Electricity from a Wind + NEISO Load Profile

Condition Modeled:
- Mass wind with ~40% capacity factor at total cost of ownership of $1,500/kW
- NEISO 2016 hourly load output at 90% annual availability
- Storage RTE of 60%

Outputs:
- Wind + Storage plant configurations that minimize LCOE
- LCOE over 20 years of output (Color map)
- Slope of contour lines gives maximum discharge rate in hours



2016 US Fossil Fuel Electricity Generation

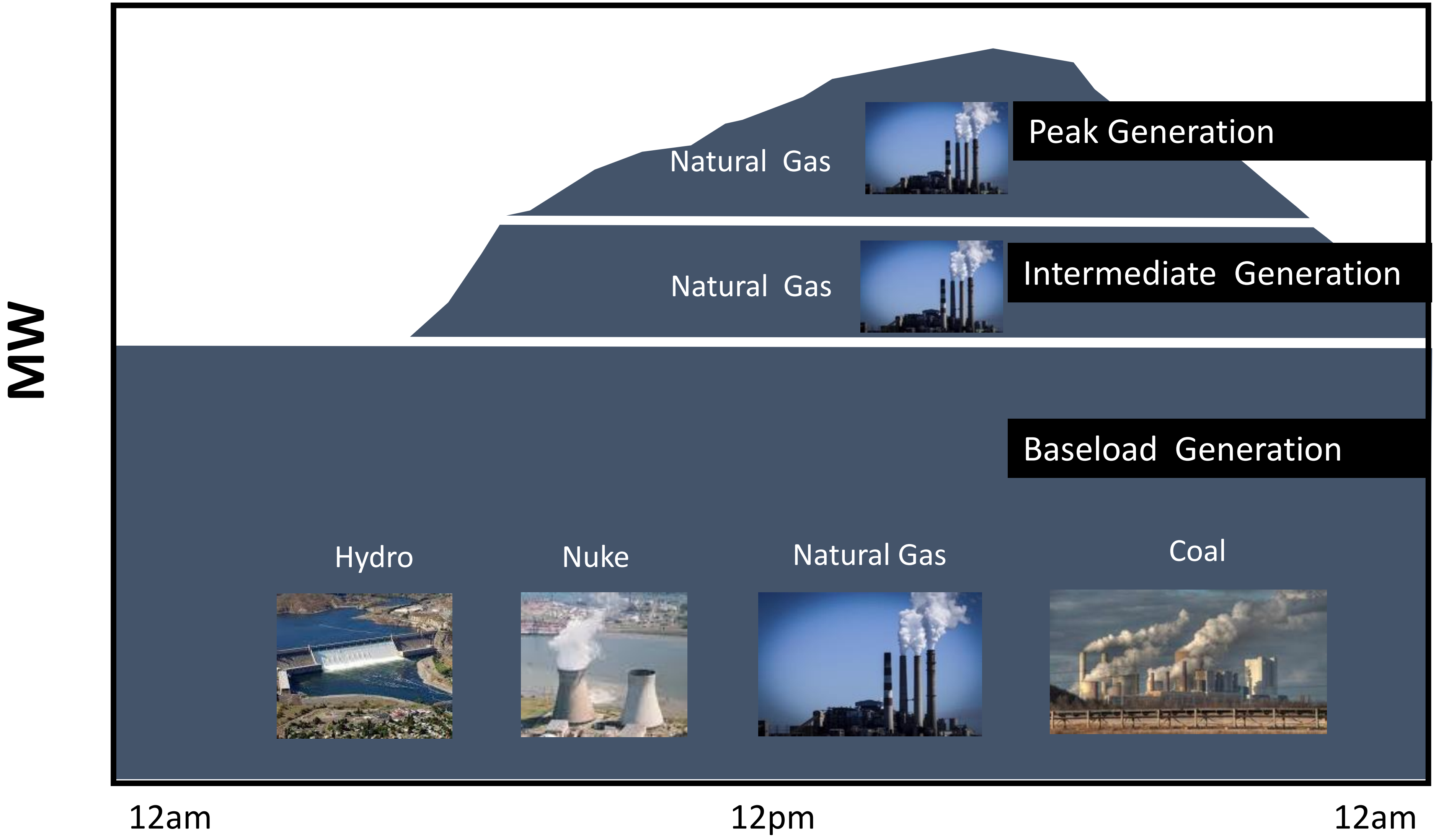
	Generation (GWh)	Capacity (GW)	% of US Capacity	Implied TAM
All US Coal	1240	289	27%	$700B
All US Gas	1380	449	42%	$1.09T
US Fossil Gen*	2620	738	69%	$1.79T

Total Addressable Market in the US for Baseload Renewables: >$700B

*Includes intermediate and peaking generation

Source: EIA

Where is Fossil Fuel Generation?



CCGT Specifications

	Units	CCGT
Installed Capital Cost	$/kW	1,230*
Variable O&M	$/MWh	3.67*
Fixed O&M	$/kW-y	6.31*
Heat Rate	Btu/kWh	6,705*
Fuel Cost	$/MMBtu	3.58**
Fuel Cost Inflation	%/y	1.6**
O&M Cost Inflation	%/y	2
Discount Rate	%/y	4
Contract term	y	20

*https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf

**https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf; Henry Hub @ $5/MMBtu in 2040